Team *Narwhal*: USNA AUV 2008

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***Abstract—Narwhal* is USNA's 2008 autonomous underwater vehicle (AUV) designed and built by undergraduate students of Systems and Electrical Engineering disciplines. It is designed to navigate a series of underwater obstacles and missions to compete at the 11th Annual AUVSI AUV Competition in San Diego. The vehicle consists of a lightweight fiberglass frame with a Pelican case housing the batteries, computer, power relay board, and electrical system. Four thrusters (two vertical and two horizontal) provide depth, pitch, and heading control. Two DVT 542 cameras provide color-based computer vision from a clear polycarbonate. Combined with an in-house sonar system, the vehicle is able to accomplish a variety of the competition objectives. Team Narwhal's goal was to improve upon the design from last year's entry by simplifying the mechanical design, upgrading the vision and sonar systems, and streamlining the computer architecture. Our system is more robust, simpler, and easier to communicate with, allowing for improved performance in less time.**

I. Introduction

Narwhal (fig 1.) is designed and built specifically to compete in AUVSI's AUV Competition against almost 30 schools this year. To successfully compete, we will have to prove our vehicle is adept at autonomously completing an array of underwater tasks designed to mimic tasks that are performed by commercial and military underwater vehicles.

Figure 1 - *Narwhal*

These tasks include:

- Passing through a gate
- Following a path on the pool floor
- Tracking a underwater buoy
- Drop markers in a bin
- Navigate through a small corridor
- Home on an acoustic pinger
- Pick up an object
- Surface within a specified zone

Most fundamental to the vehicle's success is a functioning control system that allows the vehicle to stabilize at a specified depth, maintain a constant pitch, and follow a specified heading.

More complicated but equally important to the success of the vehicle is its ability to navigate by a series of waypoints, visually acquire different objects, acquire an acoustic pinger, and to navigate the vehicle towards

those objects.

II. Mechanical Design

A. Frame

One inch pultruded fiberglass square tube was used to fabricate the chassis of the vehicle, as was done last year. A new frame was made for this year's vehicle to be simpler and smaller. The new frame is now only 36" long and 9" wide, improving the probability that it will surface entirely within the surfacing zone. In addition, the team removed the massive dorsal support strut that was in place on the old vehicle (on its underside) and left the new frame as a simple rectangle with reinforced sub attachments for thrusters. The frame was drilled with holes to allow it to flood, reducing buoyancy.

The edges of the frame are bonded with fiberglass, epoxy and triangular supports (fig. 2) to ensure that the edges were just as strong as the rest of the frame. The frame is light, yet very strong and can withstand the normal stresses of operation as well as be resilient to accidents and mishaps.

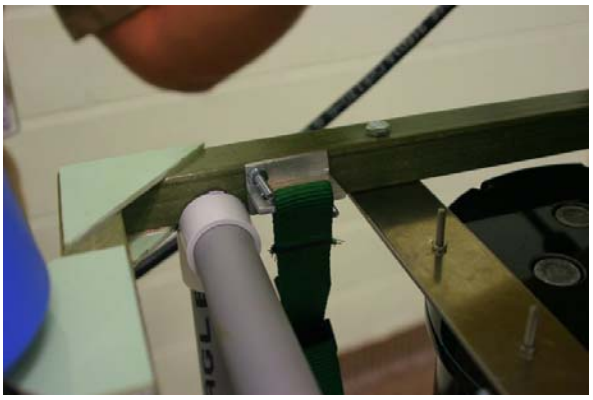

Figure 2 - Triangle Supports

B. Electronics Compartment

A model 1450 Pelican© case makes up the hull of the vehicle where the computer, battery, and electrical components are placed. The case provides watertight integrity and easy access to change the batteries and alter the wiring.

The Pelican© case was mounted with t-brackets to run straps through the underside of the frame and up to the side of the case. These brackets are made of 1/8" aluminum and have two holes placed in each. These holes are big enough to fit a #8 screw through and are used for fastening the brackets to the frame. The design is relatively streamlined (as they are placed on the inside of the frame) to minimize drag. The straps are simple hiking straps that secure the case with buckles that you would find on any generic backpack. The straps are sewn to the buckles and t-brackets. This design makes it easy to remove the case by unbuckling the straps and unscrewing the SeaCon© watertight connections

C. Thrusters

Two Tecnadyne© model 260 thrusters (fig. 3) are placed on the port and starboard sides of the vehicle to provide propulsion and heading control. Two Tecnadyne© model 300 thrusters are placed fore and aft to provide pitch and depth control and vertical propulsion.

The Tecnadyne© thrusters were selected because they are compact, watertight, and easily interface with the computer through a digital to analog converter. The separate power and control circuits in the thrusters are advantageous compared to simple DC motors, which would require a completely separate, custom power control circuit to control the speed of the motors.

Figure 3 - Model 260 Thrusters

$$C_g = \frac{(Frame_w)(x_{w1}) + (3)(Thrusters_w)(x_{w2}) + (DVL_w)(x_{w3}) + (EE_w)(x_{w4}) + (Thruster_w)(x_{w5})}{(Frame_w) + (3)(Thrusters_w) + (DVL_w) + (EE_w) + (Thruster_w)}$$

$$C_g = \frac{(1.95lbs)(18") + (3)\{(23oz)\left(\frac{1lbs}{16oz}\right)(23")\} + (4.5lbs)(27") + (5lbs)(27") + \{(23oz)\left(\frac{1lbs}{16oz}\right)(38.5")\}}{(1.95lbs) + (3)\{(23oz)\left(\frac{1lbs}{16oz}\right)\} + (4.5lbs) + (5lbs) + \{(23oz)\left(\frac{1lbs}{16oz}\right)\}}$$

$$C_b = \frac{(CamHou\sin g_b)(x_{b1}) + (PelicanCase_b)(x_{b2})}{(CamHou\sin g_b) + (PelicanCase_b)} = \frac{(2lbs)(-2.5") + (33.7lbs)(27")}{(2lbs) + 33.7lbs)} = 25.347"$$

The thruster mounts are made of pultruded fiberglass and are very simple in design. They contain a slight concave cut (fit for the radius of the thrusters) and have slits in the sides in order to accommodate the hose clamps that securely fasten the thrusters to the frame while they are in use. When mounting the thrusters on the frame, we used a simple flexible rubber material placed in between the thruster, the fiberglass, and the hose clamp. This provides protection for the thruster while it is in used from any grinding that might occur. The hose clamps have shrink wrap tubing around them to keep from scratching the thrusters.

D. Trim and Buoyancy

Last year's team had initial troubles with the vehicle's trim in the water, resulting in a large pitch angle and requiring redesign of the vehicle. To avoid this, we made trim calculations during design and prior to mounting anything to the vehicle. We knew the approximate weights and locations of all major components. After experimenting with the design on paper and going through a series of iterations, we came up with the following centers of buoyancy and gravity for the AUV:

E. Camera and Compass Housing

The camera housing (fig. 4) is an in-house project. The case is a rectangular prism made of clear polycarbonate. The lid is held on by two buckles and sealed by an O-ring coated with silicone sealant. The cameras and compass are mounted to the case using 3M double sided foam tape. Power is fed to the cameras via a SeaCon© connector installed in the lid. Communications with the cameras are accomplished via Ethernet cables through the same SeaCon©.

This location was chosen for the compass because it offers a more rigid and stable platform for the compass and isolates it from the magnetic effects of the high amperage thruster and electromagnet circuits.

Figure 4 - Camera Housing

III. Electrical Design

A. Power

Two batteries are used in the operation of the vehicle: a thruster batter for powering the thrusters and an instrumentation battery for powering everything else. The use of two batteries is the primary method of isolating the high noise thrusters from the circuitry of the sensitive sensors and computer. The batteries were selected based on compatibility between load voltages and to remain below the Navy shipboard electrical safety standard of 30 V (1).

The instrumentation battery is Li-Ion rated at 25.9V and the thruster battery is NiMH rated at 24V and 40A. The thruster battery requires such high current rating to accommodate the high starting currents of the thrusters.

B. Switching and Regulation

The kill switch is a waterproof switch that operates a relay, which is installed between the thruster circuitry and the thruster battery. It replaces a magnetic reed switch arrangement, which proved unreliable in last year's competition. The kill switch does not affect the operation of any other component.

Electrical loads are listed in table(1). Regulation is provided by a custom-built power supply board located in the vehicle's hull. Four power switching voltage regulators and associated circuitry reduce and regulate instrumentation battery bus voltage to meet component input voltage specifications levels. Fuses are also installed on this board for short-circuit protection.

Component	Input voltage (VDC)
DVL	20-60 V
Depth Cell	13-28 V
Computer	5V regulated
Compass	5V regulated
Cameras (2)	24V regulated
SONAR	12V regulated
Thrusters (4)	Main Power: 24V Control circuit: 12V regulated
Marker Dropper	25.9V

Table 1 - Electrical Loads

C. SeaCon© Connectors

SeaCon© connectors were selected for ease of installation and customization. The SeaCons© were used for all connections between thrusters, sensors, and the Pelican© case hull.

IV. Computer

A. Hardware

The computer stack is based on the Technologic TS-7200© single board computer, selected for its small size, low power requirement, extensive features, and expandability. The motherboard houses a 200 MHz ARM-9 processor, 32 MB of SDRAM, two RS-232 serial ports, two USB 2.0 ports, Ethernet port, an 8-channel 12-bit analog-to-digital converter, 20 digital input-output pins, as well as other features. In place of a disk drive, the motherboard uses a 2 GB compact flash (CF) card for file storage; significantly reducing the size of the computer and its power requirements. Additionally, the CF card can be quickly duplicated, providing a simple means of backing up the vehicle's file system. In the event of a computer hardware casualty, the computer can be quickly restored by securing computer power, installing the spare computer stack and one of the

duplicate CF cards, and powering up the computer. The computer stack draws approximately 5 watts. The motherboard also includes an 8-bit 64-pin PC-104 header, allowing installation of daughterboards to complete the computer stack.

The computer stack contains a total of 6 serial ports: 2 on the motherboard (COM 1 and COM 2) and 4 on the Technologic TS-SER4© card installed on the PC104 header (COM A, COM B, COM C, and COM D). Four of the ports are allocated to sensors: compass, Doppler velocity log (DVL), and sonar. One port is currently unused, and the sixth port is used for serial terminal connection to the computer when Ethernet is not used, either by serial cable in the lab or by Maxstream XBee© wireless communications once the hull is sealed. Table (2) summarizes communication protocols in the vehicle.

The vehicle's thrusters require an analog speed command between -5 and +5 VDC, which is provided by a Real Time Devices DM6604© D/A card. The card is connected to the motherboard via the PC-104 bus, and 4 of its 8 channels are set to -5 to +5 VDC operation and used to command the 4 thrusters.

B. Software Architecture

The software architecture is a simple design. It consists of concurrent processes that write to and read from shared memory to communicate with each other (fig. 5). All the code is written in C using a GNU GCC compiler and is run on a Debian Linux distribution. The code consists of sensor programs to read from the sensors and write to shared memory, control programs to make decisions and send command voltages to the thrusters, and a logging program to store the data in a text file. The data can be pasted directly into a Matlab© script, which can graph it all with a single click. See figure 6 for the program hierarchy.

Component	Protocol	Port
Thruster Speed Command	Analog	D/A Channels 0-3, -5V to +5V
Depth Cell	Analog	A/D Channel 0, 0V to +10V
XBee	RS-232, 115200 baud, 8n1	COM1 (TS-7200) ttyAM0
DVL	RS-232, 9600 baud, 8n1	COMB (TS-SER4) ttyS1
SONAR	RS-232, 9600 baud, 8n1	COMC (TS-SER4) ttyS2
Compass	RS-232, 9600 baud, 8n1	COMD (TS-SER4) ttyS3
Marker Dropper	Binary Logic	DIO Channels 0-1, +3.3 volts amplified to +5.5
Forward (downward) DVT	TCP/IP	131.122.80.200 (201)

Table 2 - Communications Protocols

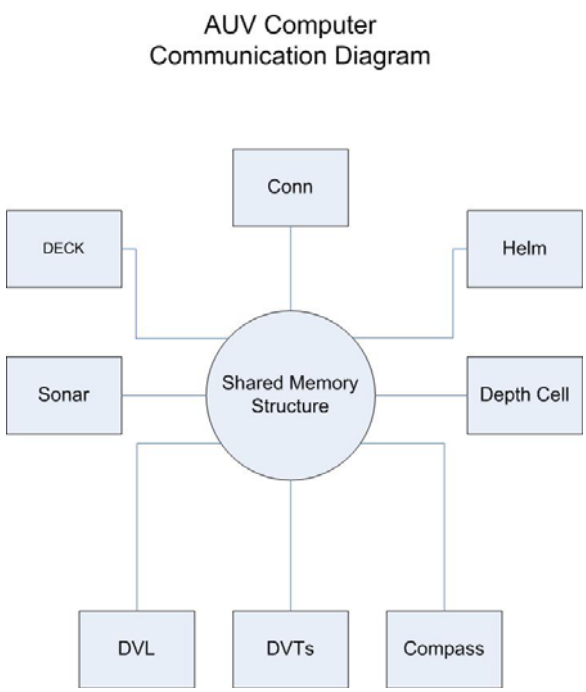

Figure 5 - Communications

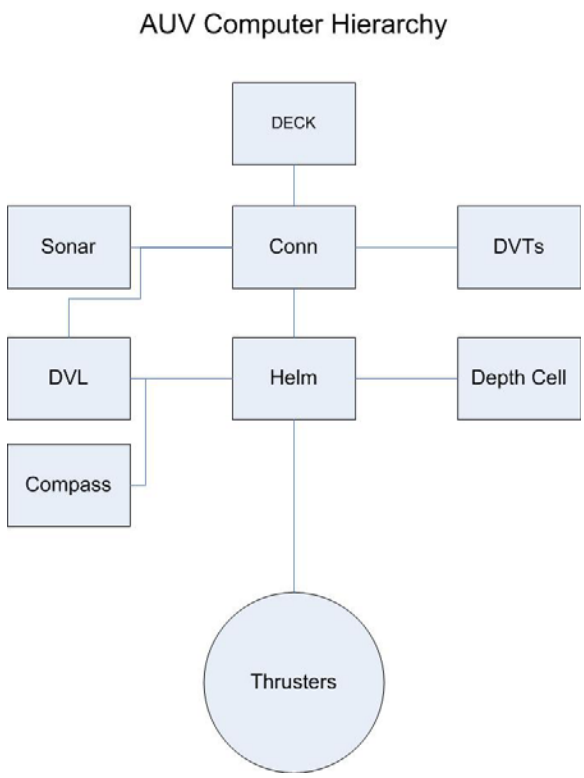

Figure 6 - Program Hierarchy

C. Communications Code

The sensor programs all act essentially the same. They open a connection to the device (serial for DVL, compass, and SONAR; TCP/IP socket for the cameras; and a reading off the ADC port for the depth cell), parse or calculate the data, and write the information to shared memory.

The socket connection for the cameras deserves special attention because of the complex nature of TCP/IP protocol and the chances of lost packets in the network. The program is robust enough to close and reopen the connection in the case of bad data and to attempt to connect multiple times if a connection attempt fails.

D. Control Code

Narwhal utilizes three primary control programs. The Helm program takes in information on depth, course, and speed from shared memory and processes inputs from the navigational sensors. Using the information from the sensors, Helm sends commands to the thrusters via the D/A card.

The depth control is a PID controller, with the derivative term averaged over ten readings to smooth out noise typical of derivative terms. The depth controller has different gain and saturation values for the forward and aft thrusters to account for hydrodynamic and buoyancy forces, allowing more controlled descent. The heading and pitch controls are both proportional.

For higher level control, *Narwhal* makes use of a conning program. Conn controls waypoint, vision, and sonar navigation by issuing course, heading, and speed commands to Helm. It takes inputs from the SONAR system, the cameras, and all navigational sensors in order to carry out mission objectives. The waypoint control calculates the necessary course from current

position and next waypoint. The camera control adjusts heading proportionately with the error given by the camera tracking system.

The Deck program gives the vehicle the highest level of control, being able to define whether the vehicle operates for a specific course, speed, and heading; homes on an object with the cameras; homes on a acoustic pinger with the SONAR; navigates via waypoints; or operates the thruster voltages independently. It can perform all five functions either manually, at the command of the user, or in an autonomous script.

V. Vision Systems

A. *Architecture*

Two Cognex 542C Legend DVT© cameras are used as forward and downward looking cameras. These cameras were chosen for their onboard image processing capability, keeping intensive processing calculations off of the main computer and allowing for fast operation, and their ability to filter images based on RGB and other values. The vision system is comprised of four "sensors" that make up a "product" – a color sensor, blob detection sensor, blob analysis sensor, and correction script. The color sensor allows the camera to "learn" a certain color in its range (fig. 7), and also allows the programmer to place thresholds in the system for variations in the image (changes in light, light angle, etc.).

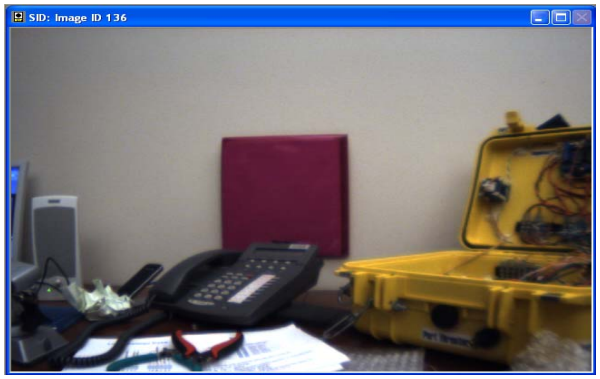

Figure 7 - Target Color

This color is then fed to the blob detection sensor, which will only detect blobs within the threshold sent by the color sensor (fig. 8). This allows the cameras to pick out specific colors – since the main targets for the cameras are both uniformly colored and stand out from the background, this is an optimal solution. The blob detection sensor sends the data of the blob to the analysis tool in order to extract the position within the camera frame and the primary angle.

Figure 8 - Blob Detection

Once this analysis is complete, a "correction" block of code translates the position into a distance from centerline and the angle into a +/- 90 degree angle off of centerline. The result is a data stream (fig. 9) fed to the computer that gives the distance in pixels from centerline of the image, the difference of angle from centerline, and area of the blob.

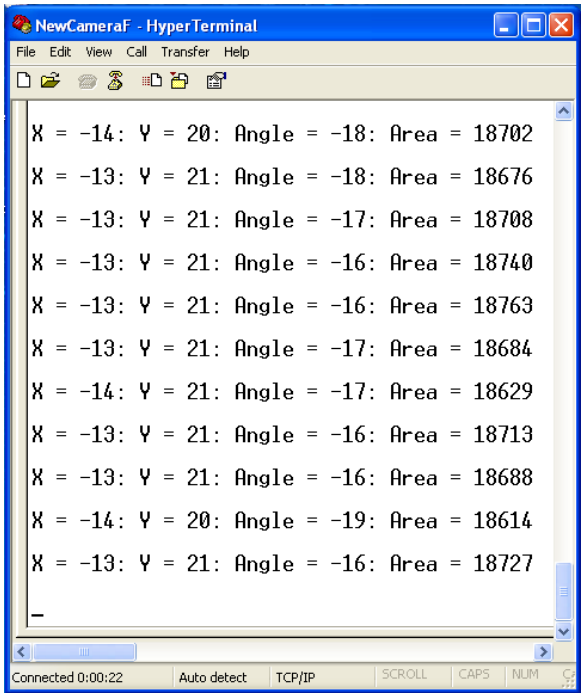

Figure 9 - Data Stream

Angle is not very crucial to the forward camera, but is the main part of the design for the downward. Area provides a measure of distance, primarily for fine control closer to the object. For simplicity's sake, we used the same code for both cameras. The only difference is the color that each camera learns prior to the competition.

VI. Sensors

A. DVL

An RD Instruments 1200 KHz Workhorse Navigator© is used as *Narwhal's* Doppler Velocity Log. It is powered directly from the battery bus voltage because of its 20-60 VDC input voltage range. The velocity measurements made are transformed into the global reference frame by compass readings and then integrated to provide a dead-reckoned vehicle position. Data is sent to the computer via serial communications.

B. Compass

Narwhal's heading reference is a Honeywell HMR3600 Micropoint© digital magnetic compass, which is mounted in the camera compartment. It allows for heading measurements accurate to within 0.5 degrees and attitude measurements up to +-80 degrees (roll or pitch). The data is used to keep the vehicle on course and on level pitch. This data is sent to the computer serially. The power for the compass's operation is provided by a 5 V bus on the vehicle's voltage regulator board.

C. Depth Cell

The Depth Cell used on *Narwhal* is a Keller America Levelgage©. This cell was chosen because it enabled us to avoid an additional hull penetration required for an internally-mounted cell. This cell (designed as a level detector for liquid storage tanks), is mounted to the frame and can be completely immersed. Therefore, it was connected to the computer via a SeaCon© connector through the pressure hull. Additionally, the depth cell has a 13-28 VDC input voltage range and therefore can be powered directly from the battery bus without regulation. Lastly, the depth cell can be purchased custom calibrated, which allows us to set an output of 0 VDC at 0 PSIG (atmospheric pressure) and 10 VDC at 13 PSIG, which corresponds to a depth of 30 feet in fresh water. This output is read by channel 0 of the vehicle computer's A/D converter.

D. SONAR

Narwhal's sonar system is broken down into two parts: the acoustic system and the signal processing system. The foundation of the acoustic system is 3 EDO© model 6166 hydrophones which are mounted externally

to the frame. These feed into a high-gain AD605 variable gain amplifier circuit and then to a band-pass filter which limits the signal to about 20-30kHz. From here the signal is sent to a 3 channel simultaneous sampling A/D converter on a dsPIC33FJ32MC202 processor. The signal also splits to a comparator with hysteresis circuit that performs an envelope detector based on a programmable threshold. This analog circuit produces an edge pulsed that can be read by an external interrupts of the signal processing system for all three channels. This hybrid signal analysis arrangement allows for both phase-differencing or TOA (Time of Arrival) to be used as the measurement method. Data is display on a Nokia color TFT screen for local visual user feedback and serially transmitted to the TS7200 computer. The SONAR system was built on a point-to-point wired board for the competition (fig. 10), but a custom PCB is being designed for future use in *Narwhal.*

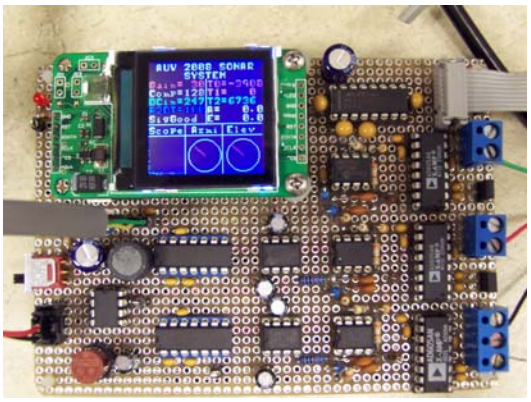

Figure 10 - SONAR Board

VII. OTHER

A. Retriever

The grabber is a simple, non-sensing design, intended to maximize the success of retrieving the target PVC pipe frame through sheer area of effectiveness, rather than precisely locating and grabbing the frame.

It is constructed from four metal rods with a spring loaded arm, attached to the vehicle in a square configuration so that the arm of one rod is resting against another.

When the vehicle descends on the target object, a simple mechanical motion of the PVC frame pressing against the arms will push the arms up into the vehicle, and when one of the pipes of the frame is far enough up, the spring action will pull the arms back down, securing the frame within the retriever.

B. Marker Dropper

The dropper is a simple, robust, electromagnetic system. The markers we drop are strong permanent magnets, and they are attached to the underside of the Pelican© case by the magnetic force between them and the iron core of electromagnets located inside the case. A short length of PVC pipe is epoxied to the underside of the case directly beneath the electromagnets, and the markers rest inside them. They offer no support to keep the markers attached, but serve simply as a protective measure against accidental bumping of the markers.

When the electromagnet is energized, the magnetic force repels the permanent magnet of the marker, ejecting it from the underside of the vehicle.

Figure 11 - Dropper

To energize the electromagnets, we have a simple circuit of the electromagnet, a resistor, and a MOSFET in series. The gate of the MOSFET is normally pulled to ground to keep it off, but it is also connected to the DIO pin of the computer. When the DIO pin is set to logic high, the MOSFET allows the flow of current, and the electromagnet energizes. It should be noted that there is a simple operational amplifier circuit between the DIO pin and the MOSFET to boost the voltage to a level that will saturate the MOSFET.

VIII. Conclusion

Narwhal has taken all the best aspects of the 2007 AUV and made them smaller, more robust, and more efficient, and built upon them by adding new capabilities in oder to fully meet the challenges at the 11th Annual AUVSI Competition; while still keeping flexibility in mind for future teams.

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References

(1) Naval Ships Technical Manual, Chapter 300

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